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Radioecological modelling of Polonium-210 and Caesium-137 in lichen-reindeer-man and top predators

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A B S T R A C T

This work deals with analysis and modelling of the radionuclides ^{210}Pb and ^{210}Po in the food-chain lichen-reindeer-man in addition to ^{210}Po and ^{137}Cs in top predators. By using the methods of *Partial Least Square Regression* (PLSR) the atmospheric deposition of ^{210}Pb and ^{210}Po is predicted at the sample locations. Dynamic modelling of the activity concentration with differential equations is fitted to the sample data. Reindeer lichen consumption, gastrointestinal absorption, organ distribution and elimination is derived from information in the literature. Dynamic modelling of transfer of ^{210}Pb and ^{210}Po to reindeer meat, liver and bone from lichen consumption, fitted well with data from Sweden and Finland from 1966 to 1971. The activity concentration of ^{210}Pb in the skeleton in man is modelled by using the results of studying the kinetics of lead in skeleton and blood in lead-workers after end of occupational exposure. The result of modelling ^{210}Pb and ^{210}Po activity in skeleton matched well with concentrations of ^{210}Pb and ^{210}Po in teeth from reindeer-breeders and autopsy bone samples in Finland.

The results of ^{210}Po and ^{137}Cs in different tissues of wolf, wolverine and lynx previously published, are analysed with multivariate data processing methods such as *Principal Component Analysis* PCA, and modelled with the method of *Projection to Latent Structures*, PLS, or *Partial Least Square Regression* PLSR.

1. Introduction

Radioecology deals with the study of pathways of radionuclides released into the environment. The endpoint is the estimation of the radiation absorbed dose and the risk of detrimental effects on various species including man. If the source is unknown, the first step is usually to collect samples at different steps on the path in question, and usually separate aquatic and terrestrial ecosystems. This presentation deals with terrestrial radioecology.

Radioecological investigations usually study the radioactivity in various samples in relation to the latitude and longitude co-ordinates as well as the time of sampling occasion. It is also important to record the fresh to dry weight ratio of the various samples, and other parameters of importance for analysing and modelling of the radioecological pathways.

The lichen-reindeer-man food chain is used as an example for dynamic modelling of radioecological concentration processes due to atmospheric fallout of ^{210}Pb and ^{210}Po.

The mathematical description of the lichen-reindeer-man pathway (L-Rd-M) in this food chain is represented by a system of linear differential equations, one for each step in the food chain (i), describing the difference between input from the previous compartment (i-1) and the elimination from (i) by the following equation (Eq. (1)):

$$dA_i/dt = \mathscr{F}(A_{i-1})[input] - A_i[output] \quad (1)$$

where $\mathscr{F}$ is the activity input function [Bq. kg^{-1}. a^{-1}] in the previous compartment A_{i-1}

Sample data of ^{210}Po and ^{137}Cs in top predators were analysed and modelled by using multivariate data processing methods such as *Principal Component Analysis* (PCA), and modelling with the method of *Projection to Latent Structures*, (PLS) or *Partial Least Square Regression* (PLSR). The method of *Partial least squares* (PLS)

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was introduced by Herman Wold (1982). His son Svante Wold, who was a chemist developed the method to be used in chemometrics, and according to him, the correct name of the method should be: *Projection to Latent Structures* (Wold et al., 1996, 2001). *Partial least square regression* modelling (PLSR) has been used in a previous work to predict missing concentration data of ^{7}Be, ^{210}Pb and ^{210}Po, at locations where only deposition values are available, and vice versa. (Persson, 2016; Persson and Holm, 2014).

Big predators like lynx, wolverine, and wolf, take up ^{210}Po and ^{137}Cs from different prey species (Gjelsvik et al., 2014, 2016). These natural and artificial radionuclides are distributed differently in muscle, liver, kidney and blood. Concentrations of ^{210}Po are higher for liver and kidney than muscle and blood. An opposite pattern is found for ^{137}Cs in muscle, with high levels in the muscle.

2. Methods and models

2.1. Lichen "L" model

The activity concentration "ACL(t)" in the top-layer of lichen "L" that is grazed by the reindeer is described by the equation:

$$\frac{dACL(t)}{dt} = DR(t) \cdot P_{SB} \cdot IF - ACL(t) \cdot (kL + \lambda); \ \left[\mathrm{Bq.\ kg_{dw}^{-1}.\ a^{-1}}\right] \quad (2)$$

where

ACL(t) is the radionuclide activity concentration in lichen at time t after deposition (Bq.kgdw^{-1})
DR (t) is the annual rate of radionuclide deposition (Bq.m^{-2}.a^{-1}); Table 1.
P_{SB} is the standing biomass density ($\mathrm{kg_{dw}^{-1} \cdot m^2}$) i.e.: Ratio of vegetation surface standing above soil to dry mass of vegetation: $P_{SB} = 0.63$ ($\mathrm{kg_{dw}^{-1} \cdot m^2}$) for lichen
IF is the *Interception fraction*, defined as the ratio of the activity retained by the vegetation A_R [Bq.m^{-2}] standing above soil to the total activity deposited A_D [Bq.m^{-2}]: IF = 1 for lichen
kL is the elimination rate constant from lichen
λ is the physical decay constant of the radionuclide in question

2.2. Reindeer "Rd" model

The model used for predicting the activity concentration "ACO(t)" in a specific organ O of a living reindeer is the annual activity concentration change in the organ O in question of the reindeer described by the following equation:

$$\frac{dACO(t)}{dt} = \mathrm{RdIL} \cdot \mathrm{ACL}(t) \cdot GIA \cdot \mathrm{ODF} \cdot BO - \mathrm{ACO}(t) \cdot (kO + \lambda) \quad (3)$$

($\mathrm{kg_{dw}.a^{-1}.kg_{bw}^{-1}}$)•($\mathrm{Bq.kg_{dw}^{-1}}$)•($\mathrm{kg_{bw}\ kg_{fw}^{-1}}$) −
($\mathrm{Bq.kg_{dw}^{-1}}$)•($\mathrm{a^{-1}}$) = [$\mathrm{Bq.kg_{fw}^{-1} \cdot a^{-1}}$]

where

RdIL is the reindeer (Rd) intake rate of lichen (L) $\mathrm{kg_{dw}}$, per bodyweight ($\mathrm{kg_{dw}.a^{-1}.kg_{bw}^{-1}}$)
ACL is the activity concentration in lichen($\mathrm{Bq \cdot kg_{dw}^{-1}}$)

Thus, the rate of consumed radioactivity is RdIL•ACL ($\mathrm{Bq.a^{-1}.kg_{bw}^{-1}}$)

GIA is the gastrointestinal absorption
ODF is the fraction of absorbed activity that is distributed to the tissue or organ O
BO is the conversion factor to activity concentration in the organ in question ($\mathrm{kg_{bw}.kg_{fw}^{-1}}$)
kO is the biological elimination rate constant of the activity from the organ
λ is the radioactivity decay constant of the radionuclide in question

2.3. The activity of ingrown ^{210}Po

The model for predicting the activity concentration of ^{210}Po "ACOPo(t)" in the fresh reindeer organ O takes into account the ingrowth of ^{210}Po from ^{210}Pb also present in the organ. This is expressed in equations (4) and (5):

$$[ACOPo(t)] = \frac{\lambda_{PO}}{(\lambda_{Po} - \lambda_{Pb})}[ACOPb_0] \cdot \left(e^{-\lambda_{Pb} * t}\right) = 1.02[ACOPb(t)] \quad (4)$$

$$\frac{dACOPo(t)}{dt} = \mathrm{RdIL} \cdot \mathrm{ACL}(t) \cdot GIA \cdot \mathrm{ODF} \cdot BO + \lambda_{Po} \cdot 1.02 \cdot ACOPb(t) - (kO + \lambda_{Po}) \cdot [ACOPo(t)] \quad (5)$$

where

ACOPo(t) is the ^{210}Po activity concentration in organ O at time t (Bq.kgdw^{-1})
ACOPb(t) is the ^{210}Pb activity concentration in organ O at time t (Bq.kgdw^{-1})

2.4. Human "M" model

The annual activity concentration change in the organ O in question of the reindeer herders consuming reindeer meat is described by the following equation:

$$\frac{dACM(t)}{dt} = \mathrm{MIRdm} \cdot \mathrm{ACRdm}(t) \cdot GIA \cdot \mathrm{ODF} \cdot BO - ACO(t) \cdot (kO + \lambda) \quad (6)$$

Table 1
Annual precipitation data and predicted value of annual deposition-rate "DR(t) of ^{210}Pb and ^{210}Po as well as the predicted and measured activity concentrations in lichen at the sampling station Lake Rogen in Sweden.

Year	Rain	^{210}Pb	^{210}Po	^{210}Pb-Predicted	^{210}Pb-Sample
	mm	Bq.m^{-2}.a^{-1}	Bq.m^{-2}.a^{-1}	$\mathrm{Bq.kg_{dw}^{-1}}$	$\mathrm{Bq.kg_{dw}^{-1}}$
1961	590	164	115	255	237
1962	567	162	113	255	244
1963	595	165	116	252	237
1964	640	168	118	256	244
1965	610	166	116	261	237
1966	650	169	118	257	289
1967	755	178	125	263	266
1968	456	153	107	276	289
1969	460	153	107	236	189
1970	560	162	113	238	241
1971	395	148	104	238	–
1972	565	162	113	251	229
Average	570	163	114	253	246
SD	93	8	5	11	27

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